



Kong, D., Cao, J., Goulianos, A., Tila, F., Doufexi, A., & Nix, A. (2018). V2I mmWave Connectivity for Highway Scenarios. In *IEEE 29th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications* (pp. 111-116). (Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC); Vol. 29). Institute of Electrical and Electronics Engineers (IEEE). <https://doi.org/10.1109/PIMRC.2018.8580735>

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V2I mmWave Connectivity for Highway scenarios

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Abstract—This paper investigates the connectivity of vehicles to road-side infrastructure (V2I) using a mmWave system at 60 GHz. Two highways in the UK were selected as virtual test drive routes. Detailed 3D geographic data of the city are incorporated into a 3D mmWave ray-tracing tool for the purpose of generating realistic channel matrices for use in an IEEE 802.11ad physical layer (PHY) simulator. The spatial and temporal multipath components of the radio channel between a road side unit (RSU) and the vehicles are modelled. Up to half million point-to-point ray tracing simulations were performed. Important parameters such as delay and angular spread for channel modelling have been extracted from the results. Statistical analysis for each route is presented. Spatial and polarimetric convolution between the multipath ray data and the appropriate beam pattern is performed in order to generate throughput predictions using a link level abstraction simulator. The throughput performance along the routes is presented for the Single Carrier (SC) transmission scheme of IEEE 802.11ad. A comparison between isotropic antennas and phased array beamforming is presented. It was found that three 60 GHz RSUs provided full coverage for a 2 km highway route. The simulation results provide a useful insight on the RSU deployment requirements.

Index Terms— mmWave, Vehicular Communications, V2I, ray tracing, 60 GHz.

I. INTRODUCTION

5G communication networks will exploit new mmWave spectrum from 24-300 GHz to meet ever-growing customer demands for high density mobile data services. For example, IEEE 802.11ad uses 2.16 GHz channels in the unlicensed 57-64 GHz band and supports data rates up to 7 Gbps [1]. Most mmWave research is currently focused around the 28 GHz, 38 GHz and 57-64 GHz bands [2].

Relative to traditional sub-6GHz spectrum, mmWave channels experience high free-space propagation loss, as well as other losses due to rain and oxygen absorption and a higher noise floor associated with broader channel bandwidth [3]. Fortunately, the use of smaller antenna elements enables the implementation of large antenna arrays to compensate for higher propagation losses [3]. In order to achieve performance gains, one or both ends of the link must utilise a beamforming antenna array. Furthermore, for mobile applications beam tracking is

necessary to maintain the link to a moving vehicle.

Vehicular applications and communication technologies are often referred to as vehicle-to-everything (V2X), which can be classified into four different types: vehicle-to-infrastructure (V2I), vehicle-to-vehicle (V2V), vehicle-to-network (V2N), and vehicle-to-pedestrian (V2P). V2X related research projects, field tests, and regulatory work have been promoted in different countries and regions [5].

Standardisation of Long Term Evolution Advance (LTE-A) based V2X is being actively conducted by Third Generation Partnership Project (3GPP) [5], which can guarantee high communication rates. Nevertheless, the maximum supported data rate is limited to 400 Mbps and end-to-end latencies cannot go below 50 ms [6]. As a result, LTE-A cannot always meet the communication requirements dictated by delay and bandwidth sensitive services such as those demanded by future Intelligent Transportation Systems (ITS) [6].

Currently commercialized mmWave systems can already ensure a system throughput in the order of gigabits per second and latencies less than 10ms [7]. These two unprecedented capabilities offered by mmWave communications make them ideal for ultra-fast and low latency communications. Apart from IEEE 802.11ad, two other standards suitable for V2X communications are the Communications Access for Land Mobile (CALM) ISO standard [8] and the forthcoming 5G New Radio (NR) [9].

IEEE 802.11ad was selected as the candidate technology for this study given the requirement of high bandwidth solutions (more than 100 Mbps) and latency in the order of few milliseconds. It is worth noting that recent train trials employing mmWave modems indicate that the IEEE 802.11ad standard can reliably operate at speeds of more than 140 km/h [10].

At the moment, proprietary technologies operating at 60 GHz based on IEEE 802.11ad are already commercially available. However, one basic and important challenge in the development of mmWave technologies is the lack of appropriate channel models. While significant studies of the channel characteristics are available in the 60 GHz band for indoor and short-range scenarios, models that can cater to channel spatial and temporal evolution in a fast-moving scenario have

yet to be developed.

In this paper we used a 3D ray-tracing tool developed at the University of Bristol, which ingests a high resolution 3D geographic database of Bristol and London (UK) including detailed structural topologies, terrain and foliage. Two V2I scenarios on highway roads with mmWave deployment were modelled. We investigated propagation characteristics and extracted important parameters for channel modelling purposes. We have also investigated the throughput performance of antenna beamforming against isotropic elements in the mmWave bands. The remainder of this paper is organized as follows. In Section II, an overview of the outdoor 3D ray-tracing tool, the link level simulator and the methodology applied are presented. Section III presents the channel statistics and throughput results. Finally, Section IV concludes the paper.

II. CHANNEL MODELLING AND SIMULATION METHODOLOGY

A. Overview of the Ray-tracing Tool and Methodology

The spatial and temporal multipath components of the mmWave radio propagation channel between a road side unit (RSU) and the vehicle was modelled using the University of Bristol's 3D outdoor ray-tracing tool [11-14]. The ray engine identifies all significant paths that travel between RSU and vehicle in 3D space, up to (in this case) a cut-off received power threshold of -150 dBm. The database includes undulating terrain and 3D buildings and foliage; all represented at a spatial resolution of 10m. Fig.1. illustrates a snapshot of the ray-tracing implementation for an example point-to-point link along one of the driving test routes within Bristol. The ray-tracing deterministic model has been previously validated for cellular and microcellular applications where the BS is located above, and well below, rooftop level. This model was recently validated at 800 MHz against measured vehicular results from real world driving test [15].

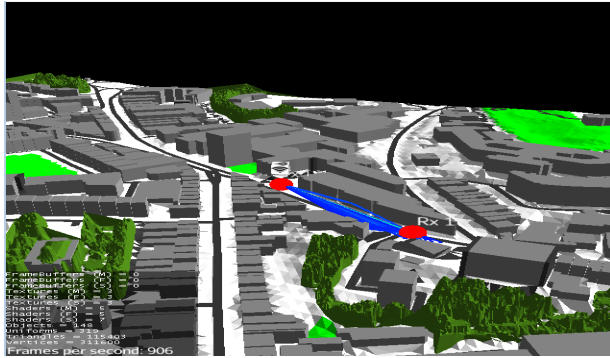


Fig. 1. Virtual 3D database and example ray structure.

To compensate for the large propagation loss at mmWave frequencies, it is essential to convolve the isotropic ray tracing channel with suitable antenna patterns, specifically beamforming patterns, from both end of the link to the resulting channels. In this work, the beamforming codebook was developed by our industrial partner Blu Wireless [16]. The modems integrate a planar array with 12×5 elements, where each of the array elements is a patch antenna. By applying appropriate phase weights at each of the array elements, the beam can be steered from -45° to 45° in the azimuth domain. The resulting antenna patterns have a Half Power BeamWidth (HPBW) of 10° . Since there are 4 antenna sectors of 90 degrees each on the vehicle unit, the whole azimuth plane is illuminated and thus beam steering is essentially applied over the 360° space. To integrate the beam patterns in the ray traced isotropic channels, an exhaustive search algorithm has been employed. According to this method, among all beams, the beam offering the strongest received signal was selected and convolved with the isotropic (point source) rays.

The methodology follows the process shown in Fig.2. The RF channel generation process exploits the electromagnetic radio propagation characteristics of the surrounding environment (i.e. buildings, foliage and terrain). The propagation prediction with isotropic elements was used for statistical analysis of the temporal and spatial parameters of the channel. Antenna patterns and codebooks were incorporated via spatial polarimetric convolution with the channel ray paths. The resulting 'beamformed' channels were used for throughput and coverage predictions with a state-of-the-art PHY simulator, which is described in section B.

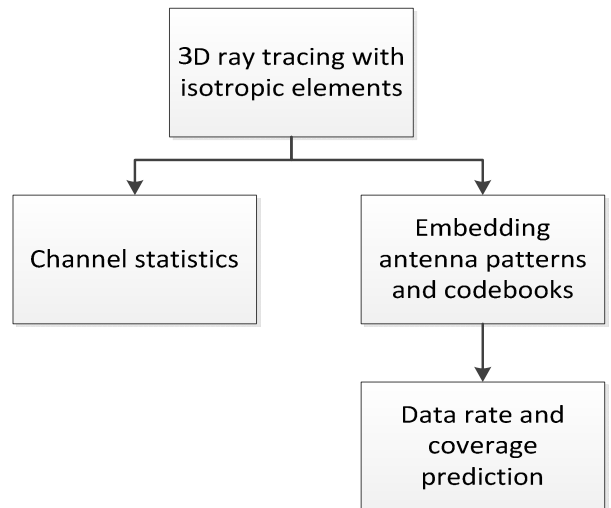


Fig. 2. Procedures followed in this paper.

B. Link-Level Abstraction Simulator

In this study, a link level simulator was used to predict system throughput. The simulator uses the Received Bit

Mutual Information Rate (RBIR) technique, which is described in [17] and used in [18]. The simulator was used as an alternative to bit-accurate PHY simulation, which is time prohibitive when the system analysis involves large number of links, modulation and coding schemes (MCS), antenna types and beamforming codebooks. The 3D complex field antenna patterns are spatially and polarimetrically convolved with the original ray tracing data. The resulting channel impulse response for each link was transformed into a wideband frequency response as an input to the abstraction engine to predict the PER and throughput for all MCS modes for the units at the vehicle. The MCS modes that maximises the throughput with less than 10% PER was chosen by the link adaptation algorithm. All the MCS modes specified in IEEE 802.11ad are supported in the simulator. The SC-PHY was used in this study. The maximum data is 4.62 Gbps using the 16-QAM 3/4 scheme [1].

C. Scenarios and parameters

In this paper two highway scenarios were selected for V2I radio channel modelling and performance prediction at 60 GHz. The routes are in Bristol and London, UK.

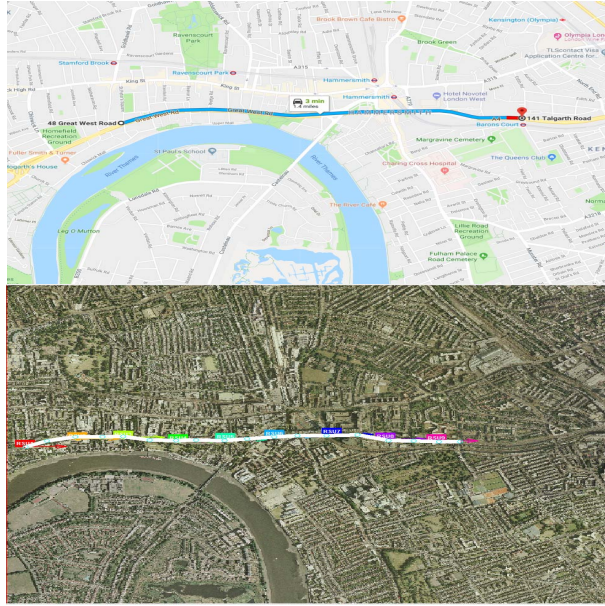


Fig. 3. Route 1 (London)

Fig.3 shows route 1 in Google Maps and the ray tracing database. Route 1 is a section of A4 road going towards central London. This route represents a highway route scenario with multiple RSUs. There are roadside trees and buildings for some parts of the route. The route length is 2076 m. There are 9 RSUs placed along the route with an experimental deployment of 250 m between adjacent RSUs.

Fig.4 shows route 2 in Google Map and ray tracer's database. Route 2 is a section of the M32 exiting the city of Bristol. It represents a highway scenario with multiple

RSUs. There are trees and buildings along parts of the route. The route length is 1208 m. There are 5 RSUs placed along the route with 250 m spacing between adjacent RSUs.

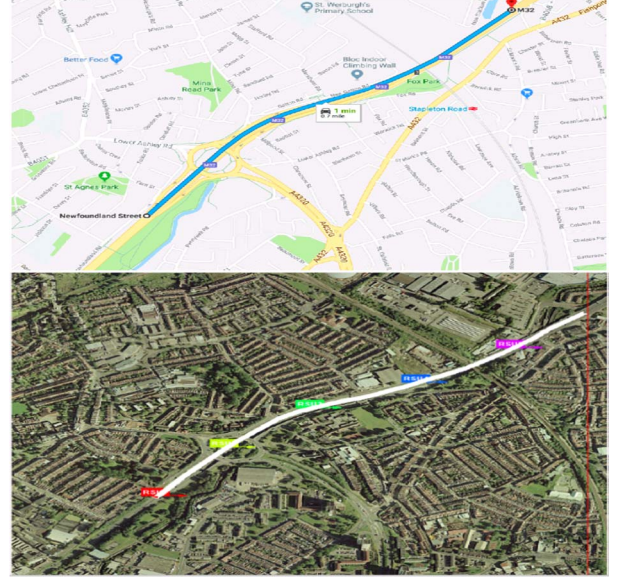


Fig. 4. Route 2 (Bristol)

Links from each RSU to vehicle locations were predicted every 5 cm for both routes. As a result, up to half million point-to-point ray tracing simulations were performed. At each point, optimal codebooks were applied at the RSU and On Board Unit. A summary of the settings is depicted in Table I.

Table I: Ray tracing modelling parameters.

System Specification	Value
Number of RSUs	5 and 9
Transmission Frequency	60 GHz
EIRP (Typhoon Modems)	40 dBm
Phased-Array Gain	18 dBi
RSUs distance (RT Simulations)	250 meters
Base Station Height	5 meters
User Equipment Height	1.5 meters
Operation Bandwidth	1760 MHz
Vehicle speed	70 mph

III. RESULTS

A. Propagation analysis

Important parameters for channel modelling were extracted from the ray tracing results and presented in this section. They include:

Isotropic path loss

The ray tracing assumes isotropic antenna elements, therefore it predicts all possible ray paths between RSUs and vehicles in 3D. Full spatial characteristics of

propagation are presented.

LoS probabilities

Less path loss is expected with LoS links compared with NLoS links. Sudden path loss increase is expected when the LoS state is lost. A link with a dominant LoS path has a higher K factor, lower delay spread and Doppler spread. Less frequency selective fading and stronger spatial consistency is expected in LoS links. It is also easier to design beamforming for LoS links due to less angular spread.

K factor and delay spread

A strong K factor represents the existence of a dominant path. The propagation will behave as a Rician fading channel. As a result, there will be less frequency selective fading and stronger spatial consistency.

Doppler spread and angular spread

In a V2X scenario, less Doppler spread is preferred because there will be stronger spatial consistency. There are less time variations with smaller Doppler spreads. Less angular spread helps with codebook design as the ray power are more spatially concentrated.

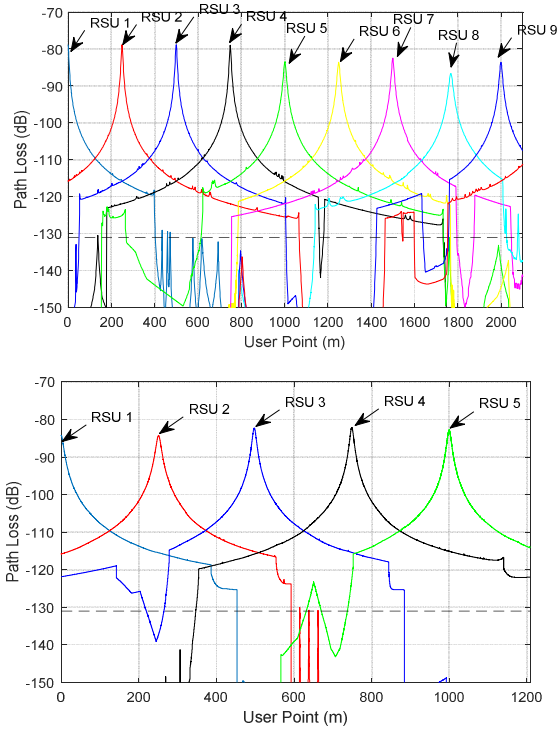


Fig. 5. Isotropic path loss for route 1 (Upper) and route 2 (lower)

Fig.5 shows the isotropic path loss from each RSU to vehicle locations for both routes. The path loss was calculated from the power summation of all the predicted multipath components (MPCs). The peaks represent the locations of the RSUs. It can be seen from both figures

that the path loss at 60 GHz decreases exponentially from 80 dB when the vehicle is closest to the serving RSU (at a distance of ~5 m) to 115 dB at 250 m from the RSU. A clear free space path loss decay profile is observed between adjacent RSUs. However, when the LoS is lost the path loss increases significantly in both routes.

Fig.6 shows the percentage of LoS links along the two routes. As expected from the path loss curves, more than 80% of the links are LoS links at both routes.

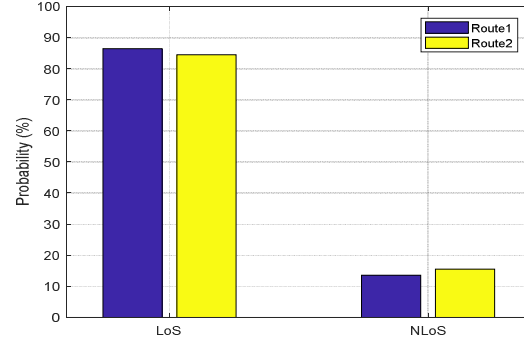


Fig. 6. LoS probability for both routes

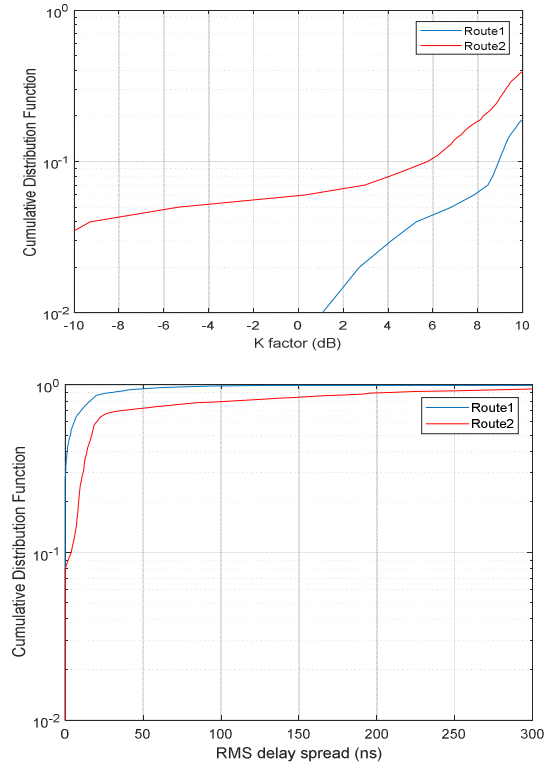


Fig. 7. CDF of K factor (Upper) and RMS delay spread (lower) for both routes

Fig.7 shows the CDF figures of the K factor and RMS delay spreads of all the links along each route. It is observed that K factors are strong along both routes. Links at Route 2 show slightly higher RMS delay spread and lower K factors. This should come from richer

scattering from the local environment. The median K factors are higher than 10 dB in both cases. Positive K factors are seen at 99% of links for Route 1 and 95% for route 2. The median values for the RMS delay spread is less than 30 ns for both routes.

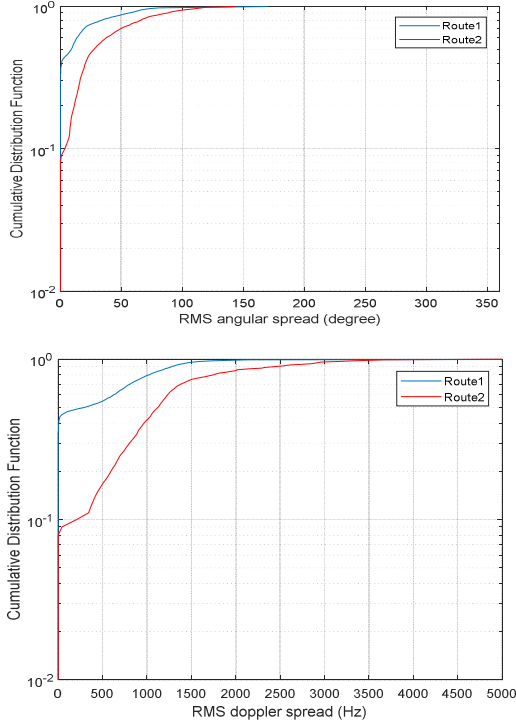


Fig. 8. CDF of RMS angular spread (Upper) and RMS Doppler spread (lower) for both routes

Fig.8 shows the CDF figures of RMS angular spread and RMS Doppler spread. Doppler spread values are based on a vehicle speed of 70 mph (UK highway speed limit). Links at route 2 show wider angular spreads, therefore higher Doppler spreads. Median value of RMS angular spread is under 50 degrees in both cases. The median RMS Doppler spread is 300 Hz for route 1 and 1100 Hz for route2. Narrow angular spreads at both routes allows the use of narrow, high gain antenna beams in order to maximise coverage.

B. Throughput Analysis

In this section, the performance of the 60GHz link-level simulations are presented. Throughput from each of the RSUs is shown to vehicle units along the routes, considering both isotropic and beam-formed channels.

Fig. 9 presents the throughput results along route 1. In total 9 RSUs have been simulated along the route, where the distance between the RSUs was set to 250 m. It can be seen that isotropic receivers have a coverage range of less than 32 meters, which is clearly impractical. When incorporating beamforming into the channel, 3 RSUs would be sufficient to maintain maximum connectivity. Given the coverage of each RSU is approximately 1200

meters, the number of required RSUs can be further reduced if the RSU locations are optimised as a pre-deployment planning task.

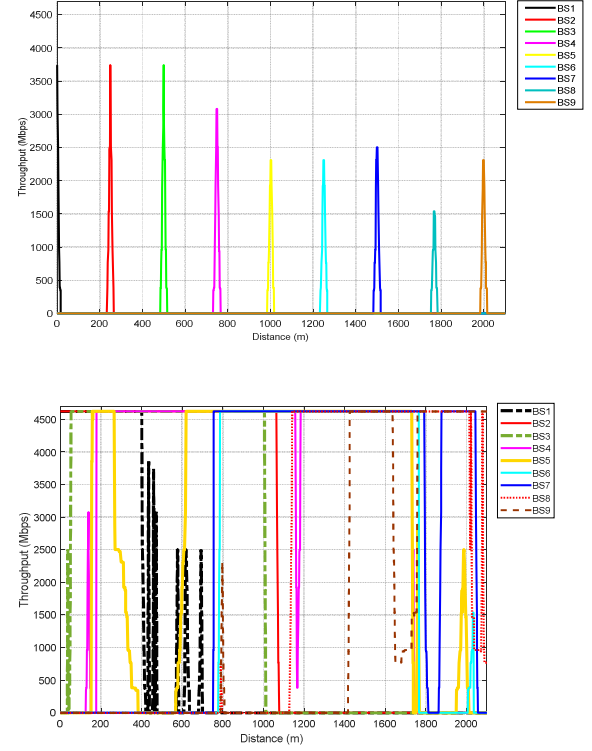


Fig. 9. Throughput versus distance for the route1 at 60 GHz; Upper: Isotropic channels; Lower: Beam-formed channels.

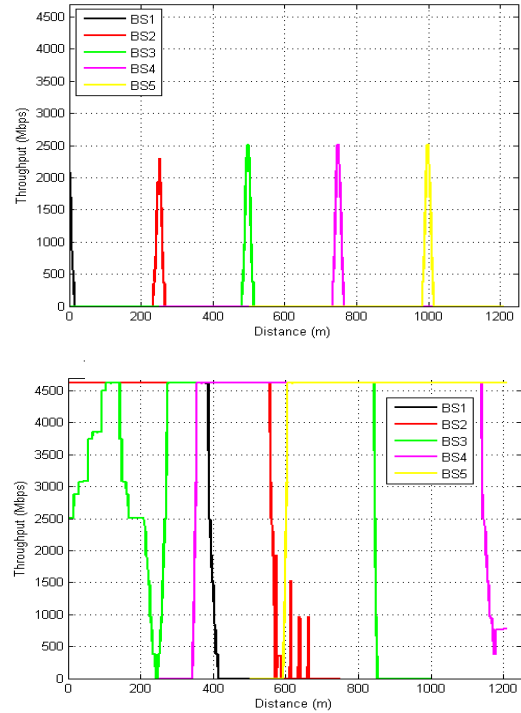


Fig. 10. Throughput versus distance for the route2 at 60 GHz; Upper: Isotropic channels; Lower: Beam-formed channels.

Fig.10 presents the throughput performance along route 2. It can be seen that isotropic receivers, have a coverage range of less than 35 meters. However, when incorporating beamforming into the channel generation process the coverage achieved is approximately 630 meters, which implies 3 RSUs would be sufficient to maintain maximum connectivity along this route. Again, the number of RSUs can be further reduced if the locations are optimised.

IV. CONCLUSION

In this paper, V2I connectivity for mmWave systems was investigated for two highway routes in the UK at 60 GHz. The spatial and temporal multipath components of the radio channel between multiple RSUs and a moving vehicle were generated and spatial convolution with the appropriate beam pattern follows used to derive the resulting spatio-temporal multipath channel. It was found that positive K factors are maintained for more than 95% of the links along both highway routes. Low RMS delay spreads (<30 ns) and narrow RMS angular spread (<50 degree) were also observed.

Throughput performance along the two routes were presented for the IEEE 802.11ad SC-PHY scheme. Throughput results clearly demonstrated that the beamforming technique significantly enhances the signal coverage and maintains maximum throughput for longer distances, hence the number of RSUs required for deployment can be reduced. It was found that three 60 GHz RSUs provided full coverage for a 2 km highway route. The simulation results and analysis have provided useful insights into RSU density and deployment requirements. The methodology presented in this work can also be applied when designing mmWave V2I systems in the future.

A channel sounding campaign is underway at University of Bristol to validate V2I propagation scenarios presented in this work. Furthermore, the interactions with mobile objectives such as cars will be considered because they can change propagation behaviors and affect radio link performance.

ACKNOWLEDGMENT

METEOR project is jointly funded by government and industry. The government's £100m Intelligent Mobility fund is administered by the Centre for Connected and Autonomous Vehicles (CCAV) and delivered by the UK's innovation agency, Innovate UK. The project was also supported by industrial partners including Jaguar Land Rover, BT and Blu Wireless.

REFERENCES

[1] IEEE 802.11ad, Part 11 WLAN MAC and PHY specification, Amendment 3: Enhancements for Very High Throughput in the

60 GHz Band, Std., 2012.

[2] T. S. Rappaport, Y. Xing, G. R. MacCartney, A. F. Molisch, E. Mellios and J. Zhang, "Overview of Millimeter Wave Communications for Fifth-Generation (5G) Wireless Networks—With a Focus on Propagation Models," in *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 12, pp. 6213–6230, Dec. 2017.

[3] S. Hur, T. Kim, D. J. Love, J. V. Krogmeier, T. A. Thomas, and A. Ghosh, "Millimeter wave beamforming for wireless backhaul and access in smallcell networks," *IEEE Transactions on Communications*, vol. 61, no. 10, pp. 4391–4403, 2013.

[4] S. Salous et al., "Millimeter-wave propagation: Characterization and modeling toward fifth-generation systems.[wireless corner]," *IEEE Antennas and Propagation Magazine*, vol. 58, no. 6, pp. 115–127, 2016.

[5] S. h. Sun, J. I. Hu, Y. Peng, X. m. Pan, L. Zhao and J. y. Fang, "Support for vehicle-to-everything services based on LTE," in *IEEE Wireless Communications*, vol. 23, no. 3, pp. 4–8, June 2016.

[6] A. Tassi, M. Egan, R. J. Piechocki and A. Nix, "Modeling and Design of Millimeter-Wave Networks for Highway Vehicular Communication," in *IEEE Transactions on Vehicular Technology*, vol. 66, no. 12, pp. 10676–10691, Dec. 2017.

[7] E. Strom, "On Medium Access and Physical Standards for Co-operative Intelligent Transport Systems in Europe," in *Proc IEEE Vol 99 No 7* pp 1183–1188, July 2011.

[8] G. Karagiannis, O. Altintas, E. Ekici, G. Heijnen, B. Jarupan, K. Lin and T. Weil, "Vehicular Networking: A survey and tutorial on requirements, architectures, challenges, standards and solutions," *IEEE Communications surveys and tutorials*, vol. 13 No 4, pp. 584 – 616, 2011.

[9] 3GPP, TR38.913, Technical Specification Group: Radio Access Networks; study on Scenarios and Requirements for Next Generation Access Technologies. V14.3, June 2017.

[10] [Online]. Available: <https://techspark.co/researchers-bring-gigabit-wireless-trains/>. [Accessed: 17/05/18]

[11] E.K. Tameh and A.R. Nix, "The use of measurement data to analyze the performance of rooftop diffraction and foliage loss algorithms in a 3-D integrated urban/rural propagation model," *IEEE 48th Vehicular Technology Conference (VTC-Spring)*, May 1998.

[12] W. Zhenyu, E. Tameh and A. Nix, "Joint Shadowing Process in Urban Peer-to-Peer Radio Channels," *IEEE Transactions on Vehicular Technology*, vol. 57, no. 1, pp. 52–64, Jan. 2008.

[13] E.K. Tameh and A.R. Nix, "A 3-D integrated macro and microcellular propagation model, based on the use of photogrammetric terrain and building data," *IEEE 47th Vehicular Technology Conference*, 1997.

[14] L. Sayer, A. L. Freire, E. Mellios, & A. R. Nix, "A Kirchhoff Scattering Model for Millimetre Wavelength Wireless Links," *12th European Conference on Antennas and Propagation (EUCAP 2018)*, London, United Kingdom, 2018.

[15] M. Charitos, D. Kong, J. Cao, D. Berkovsky, A. A. Goulianos, T. Mizutani, F. Tila, G. Hilton, A. Doufexi and A. Nix, "LTE-A Virtual Drive Testing for Vehicular Environments" in *IEEE 85th Vehicular Technology Conference (VTC2017-Spring)*, Jun. 2017.

[16] [Online]. Available: <http://www.bluwireless technology.com/mmwave-evaluation-modules/typhoon-family/> [Accessed: 17/05/18]

[17] D. Kong, "Realistic Physical Layer Performance Evaluations for Indoor and Outdoor Wireless Communication Systems," Ph.D. dissertation, Department of Electrical and Electronic Engineering, University of Bristol, UK, 2016.

[18] N. F. Abdullah, R. Nordin, A. Doufexi and A. R. Nix, "Effect of Beamforming on mmWave Systems in Various Realistic Environments," *2017 IEEE 85th Vehicular Technology Conference (VTC Spring)*, Sydney, NSW, 2017, pp. 1–5.